A DEDICATED SPACE OBSERVATORY FOR TIME-DOMAIN SOLAR SYSTEM SCIENCE.

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Summary. Time-variable phenomena with scales ranging from minutes to decades have led to a large fraction of recent advances in many aspects of solar system science. We present the scientific motivation for a dedicated space observatory for solar system science, nicknamed here the Planetary Dynamics Explorer (PDX). This facility will conduct repeated imaging and spectroscopic observations over a period of 10 years or more. PDX will execute a selection of long-term projects with interleaved scheduling, resulting in the acquisition of data sets with consistent calibration, long baselines, and optimized sampling intervals.

A sparse aperture telescope would be an ideal configuration for the mission, trading decreased sensitivity for reduced payload mass, while preserving spatial resolution. Ultraviolet capability is essential, especially once the Hubble Space Telescope retires.

Specific investigations will include volcanism and cryovolcanism (on targets including Io, Titan, Venus, Mars, and Enceladus); zonal flow, vortices, and storm evolution on the giant planets; seasonal cycles in planetary atmospheres; mutual events and orbit determination of multiple small solar system bodies; auroral activity and solar wind interactions; and cometary evolution. The mission will produce a wealth of data products—such as multi-year time-lapse movies of planetary atmospheres—with significant education and public outreach potential.

Existing and planned ground- and space-based facilities are not suitable for these time-domain optimized planetary dynamics studies for numerous reasons, including: oversubscription by astrophysical users, field-of-regard limitations, sensitive detector saturation limits that preclude bright planetary targets, and limited mission duration.

Technical requirements. The requirements for major advances in time-domain solar system science are angular resolution, sampling interval, and campaign duration. Although many ground- and space-based telescopes satisfy the angular resolution requirement, only a dedicated solar system mission could achieve the time domain requirements.

Angular resolution: Studies of planetary dynamics require the resolution of small distant objects such as cloud features, volcanic plumes, and fragments of small solar system bodies. With a ~3-m aperture, PDX will achieve an angular resolution of about 40 mas. This resolution is comparable to that provided by HST and the best current ground-based telescopes, which have demonstrated a wealth of time-domain science opportunities (see below). Beyond JWST, extremely high resolution will be afforded by very large ground-based telescopes, but PDX will not attempt to compete with those efforts, instead specifying a 40 mas resolution based on the minimum requirement to image dynamically relevant features in the solar system.

Sampling interval: Observing programs will be scheduled to ensure that each program acquires data at its critical sampling interval, which will typically range from hours to days. Occultation light curves will push the short-interval limits with millisecond-range sampling intervals.

Campaign duration: Campaign durations lasting from the entire mission lifetime to single visits will be accommodated, providing new opportunities as compared with semester- or cycle-based scheduling at other observatories. In particular, campaigns lasting the full mission lifetime will enable both high-return/high-risk science such as cryovolcanic activity surveys, as well as studies of seasonal variations in the outer solar system.

Resolution / sensitivity / mass trades. For most space telescope missions, photometric sensitivity is a major requirement. For time-domain solar system astronomy, a trade can be made between sensitivity and payload mass, since relatively bright solar system targets are less demanding of sensitivity. A sparse-aperture configuration reduces payload mass, maximizing the total aperture (and thus resolving power) for a given payload mass. Figure 1 shows the Star-9 prototype distributed aperture telescope, which demonstrated that the synthetic aperture operated at the diffraction limit of the array diameter (Rieboldt et al. 2005). Smith et al. (2005) describe the opto-mechanical design of the system.

Science programs. A wide range of time-domain research programs will be enabled by a dedicated solar system space observatory. To maximize the diversity and quality of the overall science program, the majority of observing time will consist of programs solicited from the broader solar system research community. Individual programs will be prioritized based on their scientific impact, as derived from the effective use of the resolution, sampling rate, and campaign duration opportunities uniquely provided by the PDX observatory. Programs that do not have strong time-domain constraints will receive less consideration because their goals can be met with general-purpose observatories.

A set of observing programs with complementary temporal requirements will be chosen to maximize the facility duty cycle. Table 1 gives examples of science investigations and their widely differing re-

quirements in terms of sampling interval and campaign duration. Monitoring programs will also be able to trigger shorter-interval target of opportunity observations under the appropriate conditions.

PDX will make its greatest contributions in the areas of planetary atmospheres, active geology, and small solar system bodies. A small sample of candidate investigations is given in this section; many more investigations could be persued, but these give at least a sense of the demands on sampling interval and campaign duration that are important for time-domain solar system science. Numerous science white papers are planned for submission to the 2010 Planetary Science Decadal Survey, many of which provide justification for PDX by highlighting research topics in the time domain. By relying on the broad solar system research community to contribute observing proposals, a high science return is guaranteed.

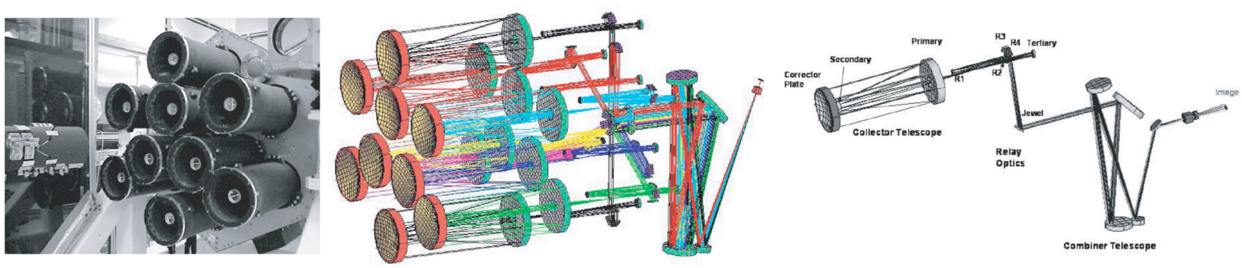

Figure 1. The Star-9 prototype distributed aperture telescope and its optical test bed at the Lockheed-Martin Advanced Technology Center (left). Telescope optical design (center). Optical path for a single element of the array (right).

Table 1. Examples of time-domain solar system science investigations that could be explored using PDX. Note that since most investigations requiring spectroscopic data also require spatially resolved spectra, an integral field spectrometer is a appropriate spectroscopic instrument choice. A distributed aperture design such as MIDAS also would enable Fizeau Fourier transform imaging spectroscopy (Smith et al. 2005). Wavelength regimes are ultraviolet (UV), optical (O), or infrared (IR).

Investigation	Category	Data type (wavelength regime)	Sampling scales	Campaign duration
Giant planet zonal winds and vortices	Atmospheres	Imaging (O)	Hours, single target rotation period	Years
Cloud/storm evolution and variability	Atmospheres	Imaging, spectroscopy (O, IR)	Hours, days	Days, years
Occultations	Atmospheres	Photometry, spectroscopy (UV, O, IR)	Milliseconds	Hours
Aurorae	Atmospheres/space science	Imaging, spectroscopy (UV)	Minutes, hours	Years, hours
Volcanic trace gases	Atmospheres/ geology/ astrobiology	Spectroscopy, imaging (IR)	Days	Years
Volcanic plumes	Geology	Imaging, spectroscopy (O, IR)	Days, hours	Years
Cryovolcanism	Geology/ astrobiology	Imaging, spectroscopy (UV, O, IR)	Days	Years
Small body mutual events	Small bodies	Photometry (O)	Milliseconds	Hours
Cometary evolution	Small bodies	Imaging, spectroscopy (UV, O, IR)	Hours	Days

Giant planet wind velocities: Cloud-tracking studies illuminate the east-west winds in giant planet atmospheres as well as the nearly geostrophic flows within coherent vortices like the Great Red Spot on Jupiter. These cloud-level velocities are primary constraints for studies in atmospheric dynamics. Data sets with sampling scales that include image pairs separated both by hours and by a single planetary rotation period provide the most accurate velocities (Asay-Davis et al. 2009). Observation campaigns on the order of a decade reveal fundamental changes such as shifts in Saturn's equatorial haze distribution and wind speeds (Porco et al. 2005) and the shrinking of the potential vorticity anomaly associated with Jupiter's Great Red Spot (Asay-Davis et al. 2009). High precision relies on measurements separated by one target rotation period, which for the giant planets is longer than a single terrestrial night, so ground-based measurements will never be able to achieve the same accuracy as spacecraft measurements. Existing data sets have large temporal gaps because space telescopes are based on single epoch observations constrained by observing cycles rather than by scientifically-determined campaign durations. Flyby and orbiter missions contribute heavily to this area, but again do not provide the extended coverage of all targets that PDX will provide.

Cloud and storm evolution: The formation and evolution of clouds and storms is central to the topic of energy transport in planetary atmospheres. For example, Mars Global Surveyor observed dust storm 2001a with high temporal resolution, providing new insights into the origin and evolution of dust storms and new constraints on global circulation models (Smith et al. 2002, Strausberg et al. 2005). In the outer solar system, New Horizons spectroscopic imaging data spanning five Jovian rotations charted the evolution of an ammonia cloud system, providing a crucial piece of the puzzle of the scarcity of such signatures in a cloud layer that is supposedly dominated by ammonia ice (Reuter et al. 2007). Similar studies with a baseline long enough to determine statistical trends would inform questions such as the transport of internal heat through convective storms (Ingersoll et al. 2000) and the pattern of belt-zone horizontal and vertical transport (Showman and de Pater 2005). Serendipity, rather than desired temporal sampling, allowed Sánchez-Lavega et al. (2008) to observe the genesis of powerful convective plumes at 23° N in Jupiter's atmosphere; these plumes were part of a poorly understood global upheaval and produced long-term changes in the upper tropospheric haze distribution (Wong et al. 2008). Clouds on Titan show intriguing variability (Schaller et al. 2006) but high-resolution observations have been available for only a fraction of a Titanian season; a dedicated PDX program would operate with a campaign duration optimized to capture seasonal variation and potentially link it to a methane cycle analogous to the Earth's hydrologic cycle. Aerosol distributions on Uranus and Neptune vary on diurnal to seasonal timescales, tracing the causes and effects of very different solar forcing and internal heat release on these otherwise similar planets (Sromovsky et al. 2003, Rages et al. 2004, Hammel and Lockwood 2007, Sromovsky et al. 2007). PDX would uniquely enable comprehensive studies of atmospheric dynamics on Uranus and Neptune by providing the temporal sampling necessary to characterize cloud and storm evolution on diurnal timescales, as well as the campaign duration needed to constrain decades-long seasonal trends.

Occultations: The density, thermal, and compositional profiles of planetary atmospheres are probed with high vertical resolution using optical and ultraviolet stellar occultations (Atreya 1986, Smith and Hunten 1990). Tenuous atmospheres can be discovered using this technique; this was how Pluto's atmosphere was unambiguously identified (Elliot et al. 1989). With vertical resolution tied directly to sampling rate, occultations drive the high-frequency sampling requirements for PDX. Space-based occultation experiments have the advantages of photometric stability and access to the ultraviolet region of the spectrum, where spectroscopic occultation observations return compositional profiles.

Aurorae: Auroral and airglow emission has been observed from the atmospheres of Jupiter, Saturn, and Uranus. Ultraviolet and near-infrared wavelengths reveal emission from H_2 and H_3^+ triggered by the influx of magnetospheric particles. The dynamics of auroral spectral and brightness distributions reveals magnetospheric interactions with the solar wind and with planetary satellites. The rapid sampling rates and extended campaign durations enabled by PDX will provide key advantages to this field, in which emission is variable on time scales of less than an hour and can vary with seasonal timescales that are decades long for the outer planets (e.g., Gérard et al. 2004).

Volcanism and cryovolcanism: Volcanic processes are either known or plausible on several rocky and icy solar system bodies. Spatially resolved multispectral photometry in the near infrared can determine the location, temperature, and size of active areas on Io (Marchis et al. 2002), which are variable on timescales of hours to months. Accurate statistics of eruption frequency could be determined with

PDX; these statistics are needed to constrain the magnitude and mechanism of Io's internal heat source. Ultraviolet stellar occultations discovered the spatially-confined cryovolcanic plumes in the south polar region of Enceladus (Hansen et al. 2006) and would be enabled by PDX for other icy bodies. The observatory could discover new cryovolcanic sources in the outer solar system on satellites and Kuiper belt objects, with a high-risk long term monitoring program that would not be feasible or appealing at other facilities. On Venus, a variable concentration of SO_2 at the cloud tops measured via ultraviolet spectroscopy hinted at potential volcanic activity, and PDX could continue with both this technique as well as with the searches for corresponding variation in the deep atmospheric SO_2 concentration, and for direct detection of thermal radiation from lava flows (Esposito 1984, Bézard et al. 1993, Hashimoto and Imamura 2001). Spatial and temporal variation of Martian CH_4 has recently been discovered, requiring either a geochemical or astrobiological origin to replenish the gas against photochemical destruction (Formisano et al. 2004, Krasnopolsky et al. 2004, Mumma et al. 2009). The temporal variability of Martian methane has not been well constrained and will help to determine the source of the gas.

Small body time-domain photometry and astrometry: Small solar system bodies reveal basic physical characteristics in photometric light curves that are modulated by rotation and by changing viewing geometry, and in astrometric image sequences of multiple systems. In some cases mutual events such as eclipses and occultations contribute as well. Sampling and campaign durations will be optimized for each object, depending on individual periods of rotation and revolution. Basic information gained from these studies will include sizes, shapes, albedos and albedo patterns, and masses and densities of multiple systems. Ground-based programs using moderate aperture telescopes have contributed greatly to this area, but fainter targets require larger telescope apertures that are limited by oversubscription. Resolving multiple systems requires them again to be bright enough to enable adaptive optics observations from the ground, whereas PDX would be able to resolve fainter and smaller targets, enhancing the statistical validity of studies of the populations of small bodies in orbit around the Sun.

Cometary evolution: Shoemaker-Levy 9 provided a spectacular example of cometary disruption, and sequential imaging was used to reconstruct the comet's fragmentation history, density, and internal structure (Asphaug and Benz 1994, Solem 1994, Sekanina et al. 1998). Since then, several other comet disruptions have revealed the diversity of internal structure, surface layering, and chemistry among cometary nuclei (Boehnhardt 2002, Kidger 2002). These factors also control fragmentation in planteary atmospheres, a key consideration for the determination of surface ages by crater-counting (Korycansky and Zahnle 2005). Accurate fragment trajectories allow measurements of competing influences such as rotation, solar radiation pressure, outgassing, and clumping. But without sufficient temporal resolution, even fragment identity (let alone trajectory) cannot be well determined. Sampling frequencies on the order of hours are ideal for resolving fragmentation events, with campaign durations of at least several days. Gas production can increase dramatically during fragmentation (Crovisier et al. 1996), allowing infrared spectroscopic observations to constrain compositional heterogeneity in the parent bodies (DiSanti and Mumma 2008). With a decade-long lifetime of the PDX observatory, several cometary fragmentation events should be observable.

Conclusion. Astronomy is currently driving advances in sensistivity and image contrast that are not generally pertinent to solar system science. Solar system science to date has advanced primarily by improving technology in the angular and spectral domains. Time-domain solar system science has shown promise, but major advances must wait for a mission designed to satisfy the constraints on this type of investigation: sampling rate and campaign duration.

The terrestrial rotation and atmosphere are a major limitation to sampling rate. For example, observations of moving clouds in Jupiter's atmosphere are ideally sampled at 10-hour intervals, but this is not feasible in a typical telescope night. Placing the observatory in space relaxes the constraint on sampling rate and enables key time domain science in the ultraviolet spectral range.

Another obstacle to optimum sampling rates and campaign durations is not imposed by technology or by the details of residing on a planetary surface. Instead, the obstacle is sociological. Observatories are scheduled to share access among their diverse scientific communities, leaving a small (but representative and fair) portion of time for the solar system research community. Programs requiring high sampling rates—as the only way to explore the time domain—usually become less competitive in this situation.

Large solar system programs of this sort are occasionally approved, but then face the next problem: meeting campaign duration requirements. Because high-capability observatories are scheduled on se-

mester or yearly cycles, programs with long campaign durations face frequent risks of termination. Programs with both high sampling rate and long campaign duration requirements are prohibitively demanding for general astronomical observatories, but would be uniquely enabled by a dedicated space observatory for time-domain solar system science.

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